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Application of Leading Edge Protuberance on Forward-swept Wind Turbine Blade for Performance Enhancement in Low Wind Regimes: A Review

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Abstract:
A review on concepts, theories and literature about wind and wind turbine technology is made. It is intended for performance evaluation of turbine blade modified by leading edge protuberance and forward sweep. Best efficiency attainable by a wind turbine is 59.3% at tip speed ratio of 7-8. Hypothesis is modifying turbine blade with leading edge protuberance and forward sweep would improve the aerodynamic performances of the turbine in low wind speed regime. From literature, airfoils with leading edge protuberances and forward swept airfoils have achieved aerodynamic advantages. Researches on leading edge protuberances on aircraft wing and other airfoil span sections have indicated decrease in lift at low angles of attack, but increase of up to 48% in lift at angles of attack beyond 16^o, and up to 44% decrease in drag or no drag penalty. The amplitude of leading edge protuberance plays significant effect in the lift and drag performances, while wavelength has negligible effect. Researches on forward swept airfoil sections identified improved performance including lower speed aircraft handling characteristic, increased resistance to span departure, and reduced stall speed for fixed wings. Also, lift and drag coefficients diminish with an increase in forward swept angles and aerodynamic characteristics for forward swept are more stable at low speed. For laminar flow wing, the reduction in sweep in the case of forward swept wing leads to more stable laminar boundary layer concerning transition because of cross flow instability and attachment. Literature reflects a consensus that forward swept geometry gives potential for the following advantages in the part load operational range of rotor blades: improvement of efficiency, increase of total pressure peak, and extension of stall-free operating range by improving stall margin. The findings of the current review suggest that investigation into wind turbine blade with leading edge protuberance and forward sweep would lead to improved aerodynamic performance of wind turbines in low wind speed regime.

Keywords: *Turbine blade, airfoil, leading edge protuberance, forward swept, aerodynamic performance, low wind speed*

1. Introduction

Wind turbine extract energy from the wind converting kinetic energy of the wind to drive the blade of a wind turbine, producing mechanical energy for direct application or electricity. Electricity generation is the most common purpose for wind turbines nowadays. Global Wind Energy Council (GWEC) puts world's total wind turbine installed generation at 369,597MW as at 2014, with 51,473MW installed in 2014 alone with an impressive 44% annual growth rate. The world's largest capacity wind turbine installed in 2014 is Vestas V164, with rated capacity of 8MW, overall height of 220m, and rotor diameter of 164m. (Vestas, 2015)

Wind turbine utilization at a location is determined by the wind quality and turbine efficiency. In order to extract the maximum kinetic energy in a low speed wind regime, turbine blade efficiency has to be optimized. So research in blade designs has been done with different levels of energy conversion (or performance). The main approach to improving the performance of wind turbine blade at any wind speed is improving its lift to drag ratio by improved aerodynamic profile of the blade, increasing angle attack, etc. In such improvements sort, challenges are encountered. For instance, increasing the angle of attack eventually forces the blade to stall. So if a technology could be developed to boost the operating angle of the blade, the prospect exists for improved wind turbine performance.

According to (Adaramola and Oyewola, 2011), Nigeria has low wind speed regimes due to its location. The wind speed varies in general from low in the south of the country to a relatively higher speed regime in the north. The variation is related in part to the latitude which increases from the south to north and vegetation distribution that change from forest region in the south to savannah region in the north. However, some areas (scattered across the country) have unusual low or high wind speeds that does not follow this general trend of wind speed distribution across the country. They also noted that while researches by (Adekoya and Adewale ,1992) and (Fagbenle and Karayiannis,1994) reported the average wind speed that ranges 2 to 4 m/s, (Fadare, 2010) reported the annual average wind speeds that range from 2 to 9.5 m/s. The wind distribution pattern for Nigeria is shown in Figure 1

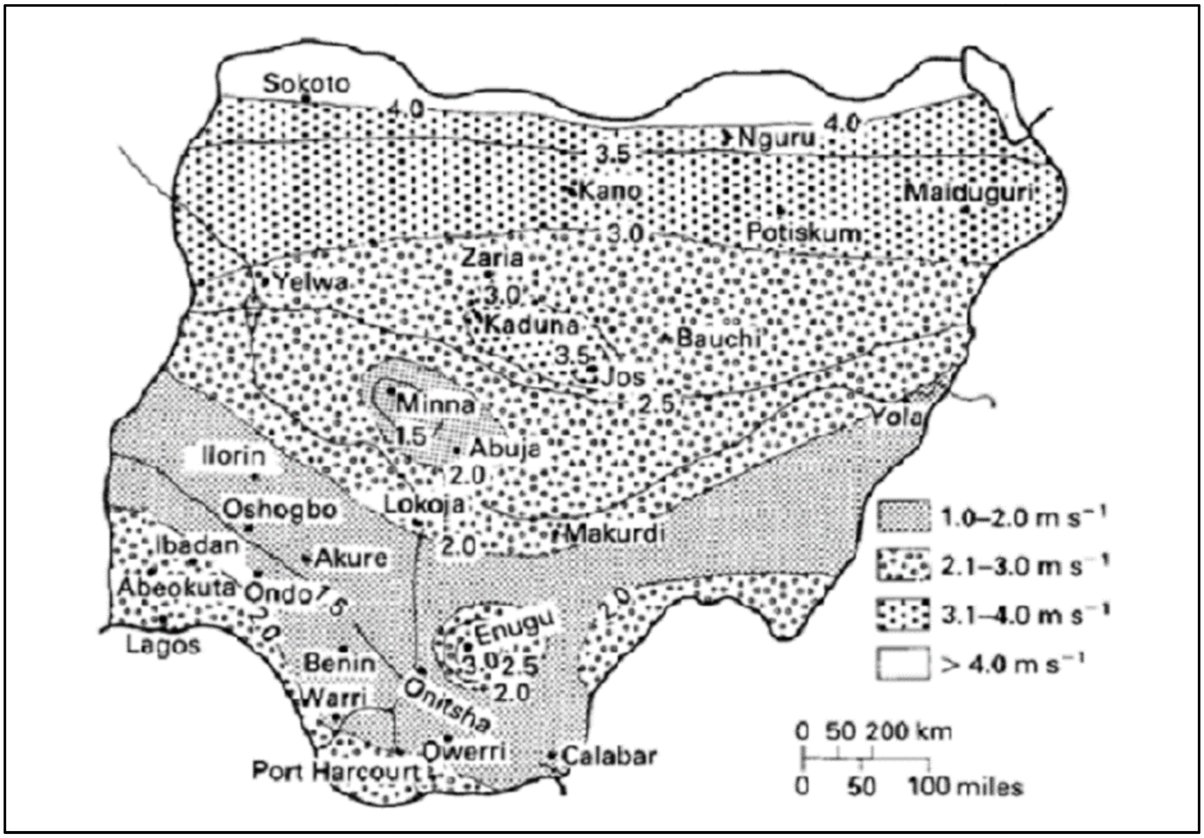

Figure 1: Nigeria annual average wind speeds distribution (isovents at 10 m height) (Ojosu and Salawu, 1990)

But bulk of wind turbines in market are not designed for low speed wind regimes like Nigeria. Installing turbines in such regimes may lead to low capacity factor and utilization. As blade is the most important component of the turbine in wind energy conversion and efficiency, research on its improvement is key to optimizing turbine performance in low wind speeds.

2. Materials and Method

Review on concepts and theories wind turbine technology is made. Past work on leading edge protuberance and forward sweep on general airfoil geometries is made. It is intended for performance evaluation of turbine blade modified by leading edge protuberance and forward sweep

3. Results and Discussion

3.1. Wind Turbine and Power Extraction

Wind turbine is a device which converts the kinetic energy from the wind to mechanical energy via a mechanical rotor. The mechanical energy can be used for water pumping, grinding or electric energy generation. The mechanical rotor is coupled to a drive train and a generator for electric energy generation.

According to rotational orientation, wind turbine can be classified as either horizontal axis wind turbine (HAWT) with blades rotating about a horizontal axis, or vertical axis wind turbine VAWT) with blades rotating about vertical axis. HAWT utilises the wind in the direction of the wind (upwind or downwind), while VAWT utilises the wind from any direction. HAWT is generally more efficient and more commonly used. Schematic of typical HAWT and VAWT is shown in Figure 2

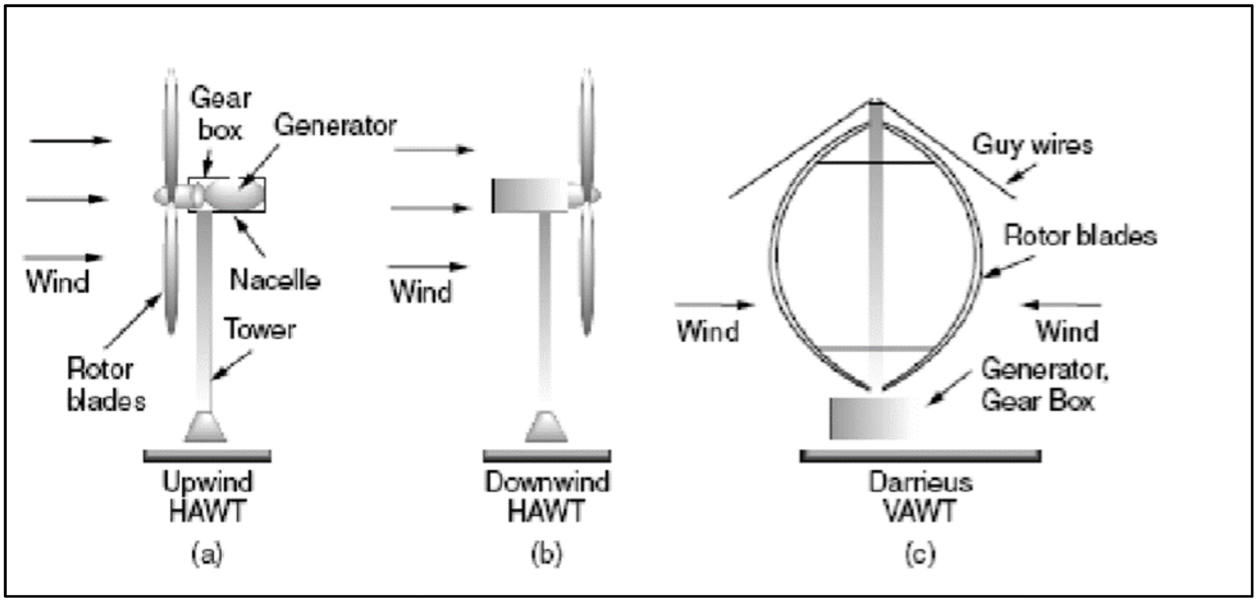

Figure 2: Types of Wind Turbines

Wind turbine converts the kinetic energy from the wind to mechanical rotational energy. As wind passes across the rotor blade, aerodynamic force (resultant of lift and drag) is created. This force turns the blade which is rigidly attached to the hub.

The power in the wind with velocity *u* impacting on a turbine with rotor blade area *A* is given by

$$P_w = \frac{1}{2}\rho A u^3 \qquad (1)$$

Since it is impossible to convert all the kinetic energy of the wind to the turbine, fraction of power extracted by the turbine denoted by power coefficient Cp gives the power of turbine as

$$P_t = \frac{1}{2}\rho A u^3 \cdot C_p \qquad (2)$$

$$C_p = \left[\frac{1}{2}(1+a)(1-a^2)\right] \qquad (3)$$

Differentiating at maximum gives a=1/3, and substituting gives C_{pmax}=16/27

In 1919 the physicist Albert Betz showed that for a hypothetical ideal wind-energy extraction machine, the fundamental laws of conservation of mass and energy allowed no more than 16/27 (59.3%) of the kinetic energy of the wind to be captured. This Betz' law limit can be approached by modern turbine designs which may reach 70 to 80% of this theoretical limit.

An important parameter relating to Betz limit is Tip Speed Ratio λ. It is the ratio of turbine blade tip speed to the wind speed.

$$\lambda = \frac{rpm \times \pi \times D}{60 \times u} \qquad (4)$$

For a given wind speed, rotor efficiency is a function of the rate at which a rotor turns. Rotor efficiency against λ for typical turbines is shown below:

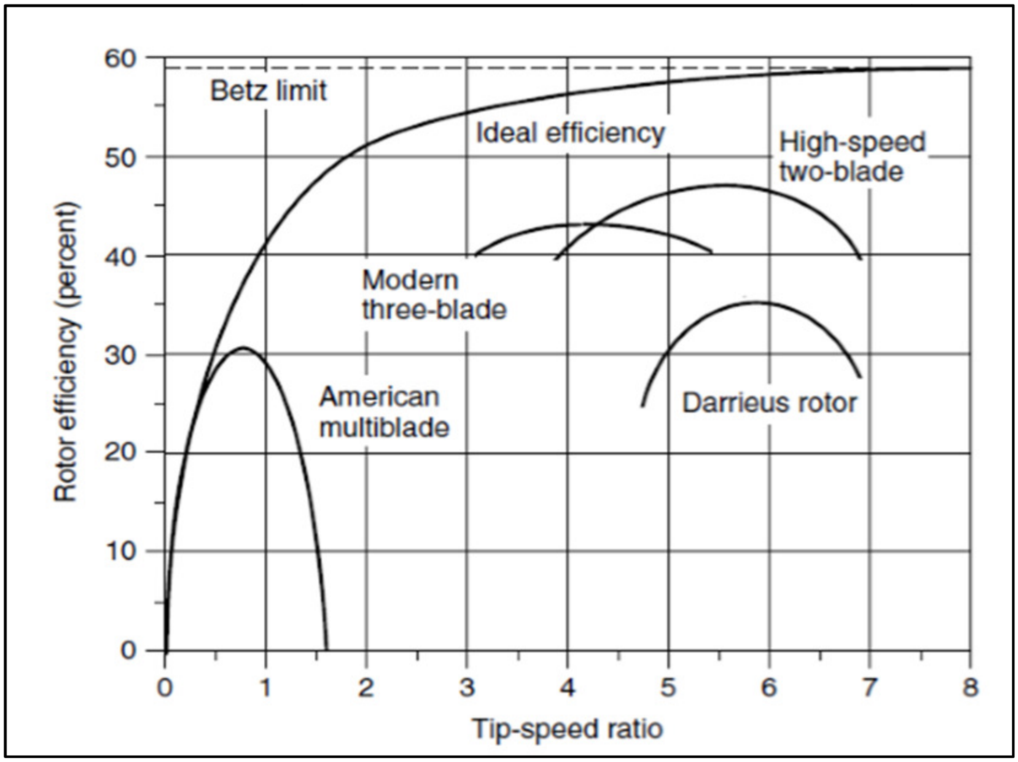

Figure 3

3.2. Blade Aerodynamics

Airfoil and Aerodynamic Forces

This is the cross sectional shape of a blade (of a propeller, rotor or turbine) or wing

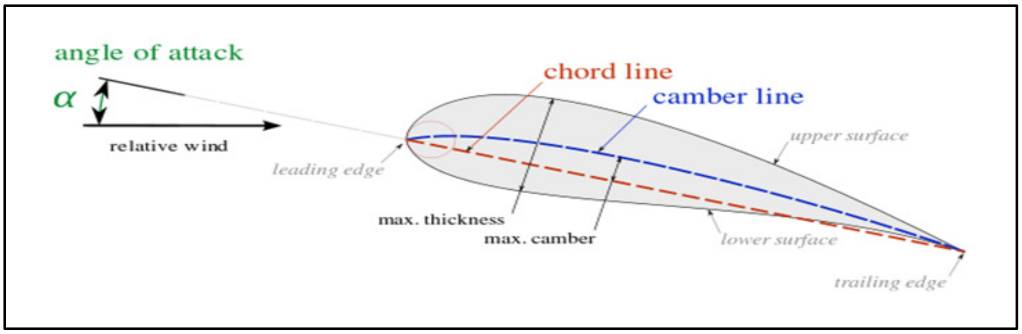

Figure 4

Motion of air over airfoil creates pressure differential between upper and lower surfaces of the blade, thereby creating a net upward force to lift the blade. The main aerodynamic forces are lift and drag. Lift is perpendicular to direction of air flow while drag is in the air flow direction.

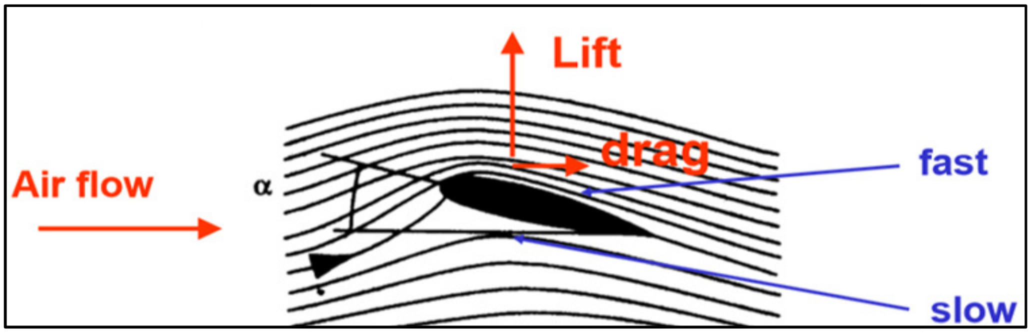

Figure 5

For a blade or wing section, lift and drag are dependent on fluid velocity u, density ρ, viscosity μ, and blade/wing area A. By Buckingham π Theorem, dimensionless parameters Lift Coefficient C_L, Drag Coefficient C_D, Reynolds Number are defined as:

$$C_L = \frac{L}{\frac{1}{2}\rho u^2 A} \qquad (5)$$

$$C_D = \frac{D}{\frac{1}{2}\rho u^2 A} \qquad (6)$$

$$Re = \frac{\rho u c}{\mu} \qquad (7)$$

3.3. Stall and Stall Control

Lift increases with increase in angle of attack α. The airfoil theory dictates that for cambered airfoil, the slope of lift coefficient versus angle of attack line is 2π units per radian.

$$C_L = C_{L_o} + 2\pi\alpha \qquad (8)$$

Stall is the situation of sudden loss in lift when angle of attack reaches a certain limit, as a result of boundary layer separation from the upper surface.

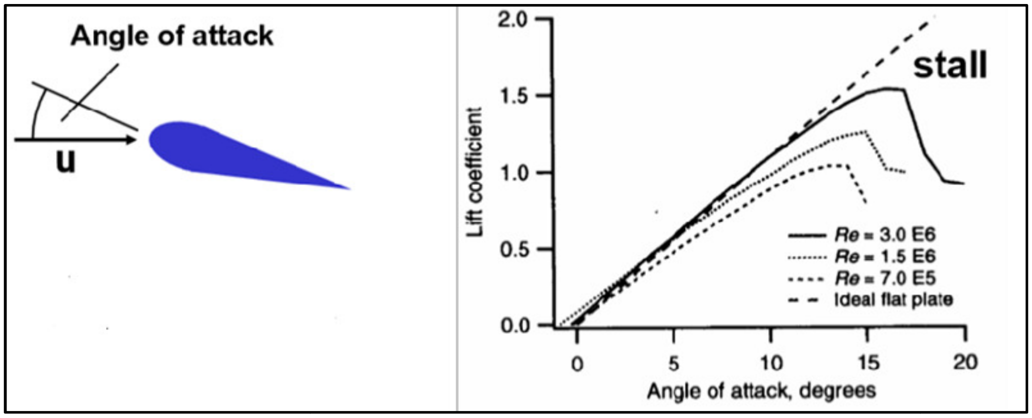

Figure 6

Stall can be controlled using active and passive devices on airfoil span sections. Active devices include retracting vortex generators. Passive devices include vortex generators and changes in leading edge contour.

3.4. Research Work on Leading Edge Protuberance

Pectoral flippers on humpback whales (Megaptera novaeangliae) make the whale extremely manoeuvrable despite its huge size. This has been attributed to the presence of protuberances or tubercles along the leading edge. There has been speculation that the protuberances along the leading edge of the pectoral flipper act as a form of passive flow control. (Custodio, 2007)

Whereas water flowing over smooth flippers break up into myriad turbulent vortices, water flow between a humback's tubercles maintain even channels, allowing the whale to keep grip on water at sharper angles and turn tight corner even at slow speeds. Morphology of the flipper was evaluated with regard to this hydrodynamic function. Except for sections near the distal tip, flipper sections were symmetrical with no camber. They had blunt, rounded leading edge and highly tapped trailing edge. Maximum thickness for cross sections varied from 49% of chord at tip to 19% at mid-span. The humpback whale flipper had a cross-sectional design typical of aerodynamic foil NACA 634-021 foil for lift generation. The morphology and placement of leading edge tubercles suggest that they function as enhanced lift devices to control flow over the flipper and maintain lift at high angles of attack (Fish and Battle, 1995).

In (Miklosovic et al., 2004), wind tunnel measurements on a scale model of an idealized humpback whale flipper with and without leading edge tubercles demonstrated the fluid dynamic improvement tubercles make, such as delay in stall angle by approximately 40%, while increasing lift 8%and decreasing drag 32%.

To examine the effects of protuberances on hydrofoil performance, the lift, drag, and pitching moments of two- dimensional hydrofoils with leading edge sinusoidal protuberances were measured in a water tunnel and compared to those of a baseline NACA 634-021 hydrofoil. The amplitude of the protuberances ranged from 2.5% to 12% of the mean chord length and the span wise wavelengths were 25% and 50% of the mean chord length. This corresponds to the morphology found on the leading edge of humpback whale's flippers. Flow visualization using tufts and dye was also performed to examine the near surface flow patterns surrounding the hydrofoils. At angles of attack lower than the stall angle of the baseline the modified foils revealed reduced lift and increased drag. However, above this angle the lift generated by the modified foils was up to 50% greater than the baseline foil with little or no drag penalty. The amplitude of the protuberances has a large effect on the performance of the hydrofoils whereas the wavelength has little. Corroborating lift and drag measurements, visualizations show attached flow on the peaks of the protuberances and separation in the valleys at angles beyond the stall angle of the baseline foil.

(Miklosovic et al, 2007) extended their original (2004) wind tunnel testing to a range of Reynolds numbers from 5.34×10^5 to 6.31×10^5, and included testing both semi-span and full-span prototypes each with, and without, sinusoidal leading edge bumps or tubercles. This work showed that the behaviour of the fluid flow for foils with leading edge bumps is significantly different between the “infinite” and “finite” wing cases. Specifically, that flow over tubercles is intrinsically three dimensional, and that the benefits of tubercle foils only are manifest in 3-D. They noted that the generation of vortices by the scallops was beneficial only to 3-D planforms in the range of Reynolds numbers tested.

In similar study, (Malipeddi,2011) examined the effect on leading edge modification of wing at low Reynolds number (Re), since low Re flows have unique characteristics. Simulations were executed on wings with leading edge sinusoidal protuberances, in order to compare the lift and drag characteristics with that of a wing with smooth leading edge. All wings had same had the same cross section of NACA2412 and a simulated Reynolds number of 5.7×10^5. Results from numerical simulation revealed a decrease in lift and increase in drag at low angles of attack in all cases of modified wings. At higher angles of attack ($>16^o$), the lift of the modified wings was up to 48% greater than that of baseline wing, with 44% less drag or no drag penalty. The amplitude of protuberances significantly affects wing performance, while wavelength has no effect.

The effects of adding leading edge sweep on humpback whale flipper models with protuberances have also been investigated. (Murray et al., 2004) reported an enhanced aerodynamic performance with increasing sweep angle.

Design and simulation of a whale-inspired blade by incorporating the bumps on to blade leading edge to determine the differences in the associated turbulent flow field, boundary layer attachment, and pressure gradients that cause lift and drag compared to traditional horizontal axis wind turbine using computational studies was carried out by (Krause and Robinson, 2009) . It is shown that a whale-inspired blade offers the possibility of an improved design at higher angles of attack. The blade is characterized by a superior lift/drag ratio due to greater boundary layer attachment from vortices energizing the boundary layer. In their investigation, two geometrical shapes of the bumps where studied, the horizontal and the vertical bumps. In the horizontal bumped blade, the area of material removal was made on top of the blade and extruded vertically through the leading edge of the blade. In the vertical bumped blade, the area of material removal was made on the face of the leading edge and extruded horizontally into the blade. The analysis of the results showed that the horizontal bump blade holds promise at a high angle of attack due to its improvement in the lift/drag ratio caused by indicated vortex formation behind the bumps. Streamlines imply a more attached boundary layer near the trailing edge of the blade. The coefficient of pressure gradient indicates that at 20° angle of attack the horizontal bumps blade was achieving a greater pressure difference than the control and vertical bumps blade. The vertical bumped blade showed potential from a design standpoint, but has inconsistent and discouraging results upon simulation.

3.5. Research Work on Forward Swept Blades

Potential benefits with forward swept wing gliders and aircraft identified include improved low speed aircraft handling characteristic, increased resistance to span departure and reduced aircraft stall speed (DLR,2008).

(Siouris and Qin, 2007) found that since sweep produces effects that vary with cos, the same result may be yielded with high speeds in the subsonic Mach number region attainable. They also found that sweeping wing either forward or aft (backward) delayed the rapid increase in transonic drag to higher Mach numbers. For laminar flow wing, the reduction in sweep in the case of forward swept wing leads to more stable laminar boundary layer concerning transition because of cross flow instability and attachment.

In their theoretical and experimental study of a forward swept wing, (Hassan et al., 2010) concluded that aerodynamic characteristics for forward swept are more stable at low speed, as forward swept provides a wide useful angle of incidence range. Also, lift and drag coefficients diminish with an increase in forward and backward swept angles, but it is less in forward swept angle.

Research on forward sweep on rotor blades has been carried on also. Literature reflects a consensus that forward swept geometry gives potential for the following advantages in the part load operational range of blades: improvement of efficiency, increase of total pressure peak, and extension of stall-free operating range by improving stall margin (e.g. Yamaguchi et al., 1993; Beiler, 1996; Beiler and Carolus, 1999; Corsini and Rispoli, 2004;Clemen et al., 2004).

In numerical analysis of 3-dimensional flows of axial fan rotor blades skewed circumferentially and chord-wisely, (Beiler and Carolus, 1999) also validated their results experimentally to lead to design of forward swept blades that exhibited good aerodynamic performance. The sound power level also improved. In numerical investigation on use of sweep as a remedial strategy to control aerodynamic limits in low speed axial fan rotors, (Corsini and Rispoli, 2004) studied two rotors with identical nominal design parameters and with 35^o forward swept blades and unswept blades respectively. They concluded: analyses of 3-dimensional flow structures showed that, sweeping forward blade, the non-free vortex spanwise secondary flows are attenuated, and a control on the onset of stall is recovered. Moreover, the swept rotor features a reduced sensitivity to leakage flow effects. Consequently it operates more efficiently approaching the throttling limit. Nevertheless, the research results are diversified regarding judgement of performance and loss modifying effects of forward sweep at flow rates near design point. (Clemen and Stark, 2003) pointed out that generally forward sweep near the tip gives a potential for reduction of near tip losses. Sweep effect is often confined to the vicinity of the endwall (the tip region) if the endwall is intended to be controlled by means of sweep.

Comparative case studies carried out by (Kwedikha, 2009), incorporating isolated axial flow rotors with swept as well as skewed blades, considered as representative examples of industrial turbo machinery rotor configurations. Incompressible flow has been assumed. The studied bladings were of relatively low aspect ratio (AR). He implied that sweep or skew, even if it is confined to the near endwall regions, influences the blade aerodynamics along the entire span

3.6. Discussion on Findings

The Betz' law limit can be approached by modern turbine designs which may reach 70 to 80% of this theoretical limit. So with more improvements, the possibility of closer approach to the limit is realistic. The prominent losses highlighted in the reviews include stalling with its associated phenomena and tip losses/leakages in both wings and rotary blades. Aside Betz limit of 59.3%, tip losses impact loss on lift coefficient when tip speed ratio changes. (Jiang, 2014) for instance determined 2 to 6% loss of lift coefficient for tip speed ratio change from 10 to 4.

The derivation of the Betz limit and tip loss assumptions shows simple analysis of wind turbine aerodynamics. In reality there is a lot more. A more rigorous analysis would include wake rotation, the effect of variable geometry. The effect of airfoils on the flow is a major component of wind turbine aerodynamics. Within airfoils alone for instance, the wind turbine aerodynamicist has to consider the effect of surface roughness, dynamic stall tip losses, solidity, among other problems.

The literature reviewed were mostly associated with wings, hydrofoil devices, gas turbines and compressors. But these devices have similarities as well as differences with wind turbines. They are similar with fact that they are airfoil devices all subjected to characteristic reaction turbine flow/power behavior. Their differences are in speed and operating conditions. They also have different airfoil profiles and aspect ratios.But fluid flow characteristics in one could indicate a pattern of behavior to be expected in another, with consideration of varying operating condition and body geometry.

There are similarities in result outcomes in leading edge protuberance studies. They indicate drag and reduced lift in low angles when compared to baseline smooth airfoil section. The increase in lift, delayed stalling and reduced drag properties are exhibited at high angles of attack. The studies concur on significant increases in angle of attack before stall. The airfoil sections of wings and turbines have similar geometric features. Even though turbine blade fluid flow is rotary, the lift and drag characteristics are similar, and studies on wing are useful and relevant to turbine blade.

The leading edge protuberance studies also indicate that the present research should focus on angles of attack range of closely lower than 16^o to values higher, as low angles have concluded unfavourable outcomes.

The forward swept wing and blade studies have similar result of efficiency increase by spanwise secondary flow attenuation, tip loss and stall speed reduction. Both outcomes could be relevant to present study of wind turbine blade in low wind speeds.

4. Conclusion and Recommendation

The review of literature has established theoretical limit of 59.3% efficiency possible for a wind turbine. It has found present wind turbines attain 70 to 80% of this value with good design and wind conditions. Low wind speed regimes like Nigeria would have operating efficiencies much lower.

The derivation of the Betz limit and tip loss assumptions shows simple analysis of wind turbine aerodynamics. In reality there is a lot more. A more rigorous analysis would include wake rotation, the effect of variable geometry. The geometry effects of leading edge protuberance on airfoil sections and forward sweeping them was searched and found in literature for wings, hydrofoils, turbines and compressors. Researches on leading edge protuberances on aircraft wing and other airfoil span sections have indicated decrease in lift at low angles of attack, but increase of up to 48% in lift at angles of attack beyond 16^o, and up to 44% decrease in drag or no drag penalty. The amplitude of leading edge protuberance plays significant effect in the lift and drag performances, while wavelength has negligible effect.

Researches on forward swept airfoil sections identified improved performance including lower speed aircraft handling characteristic, increased resistance to span departure, and reduced stall speed for fixed wings. For turbines and compressors, improvement of efficiency, increase of total pressure peak, reduction of near tip losses and improved stall margin were found as benefits.

4.1. Recommendation

The following recommendations are made:

i- Study be carried out on the effect of leading edge protuberance on airfoil sections in low wind speed regimes (low Reynolds Number flows) for application to appropriate wind turbines.
ii- Study be carried out on the effect of forward swept airfoil sections in low wind speed regimes (low Reynolds Number flows) for application to appropriate wind turbines.
iii- Study on combined effect of leading edge protuberance and forward swept airfoil section for possible optimal designs of turbine blades with these characteristics.

4.2. Significance

Investigations on leading edge protuberance and forward sweep in wind turbine blade with would lead to improved aerodynamic performance of wind turbines in low wind speed regime.

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